Introduction: groundwater resources modelling: a case study from the UK

M. G. SHEPLEY[1,4]*, M. I. WHITEMAN[2], P. J. HULME[1,5] & M. W. GROUT[3]

[1]*Environment Agency, 10 Warwick Road, Olton, Solihull B92 7HX, UK*

[2]*Environment Agency, Rivers House, 21, Park Square South, Leeds LS1 2QG, UK*

[3]*Environment Agency, Kingfisher House, Goldhay Way, Orton Goldhay, Peterborough PE2 5ZR, UK*

[4]*Present address: AMEC Environment & Infrastructure, 505 Woodward Avenue, Unit 1, Hamilton, ON, L8H 6N6, Canada*

[5]*Present address: pjHYDRO Ltd, 26 Bodmin Avenue, Stafford, ST17 0EF, UK*

**Corresponding author (e-mail: martin.shepley@amec.com)*

Groundwater has been used in the UK as a source of drinking water for centuries. For example, certain springs have been used to supply small urban areas for more than a thousand years. However, extensive use of groundwater began during the industrial revolution that started in the eighteenth century. The technology from the industrial revolution provided the means to access greater quantities of groundwater. Nevertheless, probably the more important factor was the increasing urbanization, with industrial cities such as Birmingham, Liverpool and Nottingham expanding at a phenomenal rate. With the higher population came an increased demand for water, which could be provided from local aquifers.

The trigger for extensive exploitation was the 1848 Public Health Act that required local authorities to ensure a source of clean drinking water. From 1850 onwards, large red-brick Victorian pumping stations (Figs 1 & 2) started to appear on the outcrops of the principal aquifers in England, and abstraction steadily increased until the 1990s. In 2003, the use of groundwater in England and Wales was *c.* 6400 Ml/day (6 400 000 m^3/day), of which *c.* 5000 Ml/day was for public supply (Environment Agency 2006), comprising about a third of the total drinking water supply in England and Wales. The abstraction is predominantly from the Chalk and Permo-Triassic Sandstone (Fig. 3), which account for 60 and 25% of total groundwater abstraction, respectively (Downing 1998). Outcrops of these two aquifers are located mainly in the SE and Midlands of England, where groundwater often accounts for over 40% of public supply and sometimes exceeds 70% (Downing 1998). Groundwater use in Scotland and Northern Ireland is much lower, at *c.* 60 and *c.* 110 Ml/day, respectively, representing 3 and 7% of public supply in those parts of the UK (Downing 1998).

A need to understand, quantify and predict groundwater flow in aquifers was a natural consequence of the onset of widespread exploitation of the principal aquifers in the mid-nineteenth century. The development of the science of hydrogeology in the UK over the last 200 years has been documented in detail in the excellent book by Mather (2004). Downing (2004), one of the papers in Mather (2004), describes the beginning of groundwater modelling in the UK in the late 1960s to early 1970s, both electrical analogues and numerical. The thread of this story is picked up by Rushton & Skinner (2012).

Modelling history of the UK

Since the early 1970s there has been a slow but steady increase in the use of groundwater models in the UK, and it is still increasing to the present day. Rushton and Skinner provide a brief review of the development in England and Wales, where the models were initially developed as bespoke computer programs by academics and research institutes. Now much work is done by consultants using standardized, widely available groundwater modelling codes such as MODFLOW (McDonald & Harbaugh 1988).

The development of groundwater models in the UK, as Rushton and Skinner describe, has been influenced by legislation and the organizations that have been responsible for groundwater management. In 1988, the possibility of competing groundwater models arose in England and Wales

From: SHEPLEY, M. G., WHITEMAN, M. I., HULME, P. J. & GROUT, M. W. (eds) 2012. *Groundwater Resources Modelling: A Case Study from the UK*. Geological Society, London, Special Publications, **364**, 1–6. http://dx.doi.org/10.1144/SP364.1

Fig. 1. The Bratch groundwater pumping station, built in Victorian gothic style by the Bilston Corporation, 1895 (courtesy of Friends of The Bratch).

with the advent of a separate government water regulator (the National Rivers Authority, followed in 1996 by the Environment Agency) and privatized water suppliers.

Fig. 2. Vertical triple expansion steam engine at The Bratch (courtesy of Friends of The Bratch).

The national modelling programme of England and Wales

The need for a national framework of groundwater modelling was in part a consequence of this split, which led the Environment Agency to embark at the end of the 1990s on a large programme to develop conceptual and numerical models of the principal bedrock aquifers of England and Wales and their associated superficial deposits. This programme consisted of eight regionally based sub-programmes (SW, Southern, Thames, Anglian, Midlands, Wales, NW and NE) covering the Chalk, Permo-Triassic Sandstone, Jurassic Limestone, Carboniferous Limestone, Permian Dolomites (Zechstein) and Lower Greensand (Fig. 3), described by Whiteman *et al.* (2012*a*). The work forthcoming from this programme over the period 1998–2009 forms the basis of this book. The case study and review papers in this volume that are partly or directly associated with this programme are: Black & Black (2012); Black *et al.* (2012); Daily *et al.* (2012); Gellatly *et al.* (2012); Hulme *et al.* (2012); Hutchinson *et al.* (2012); Ingram *et al.* (2012); Quinn *et al.* (2012); Shepley & Soley (2012); Soley *et al.* (2012*a*, *b*); and Taylor *et al.* (2012).

In some cases the papers provide alternative approaches to conventional groundwater modelling, because of the importance of flow in large conduits (Ingram *et al.* 2012) or time/cost constraints (Hulme *et al.* 2012). However, the papers from

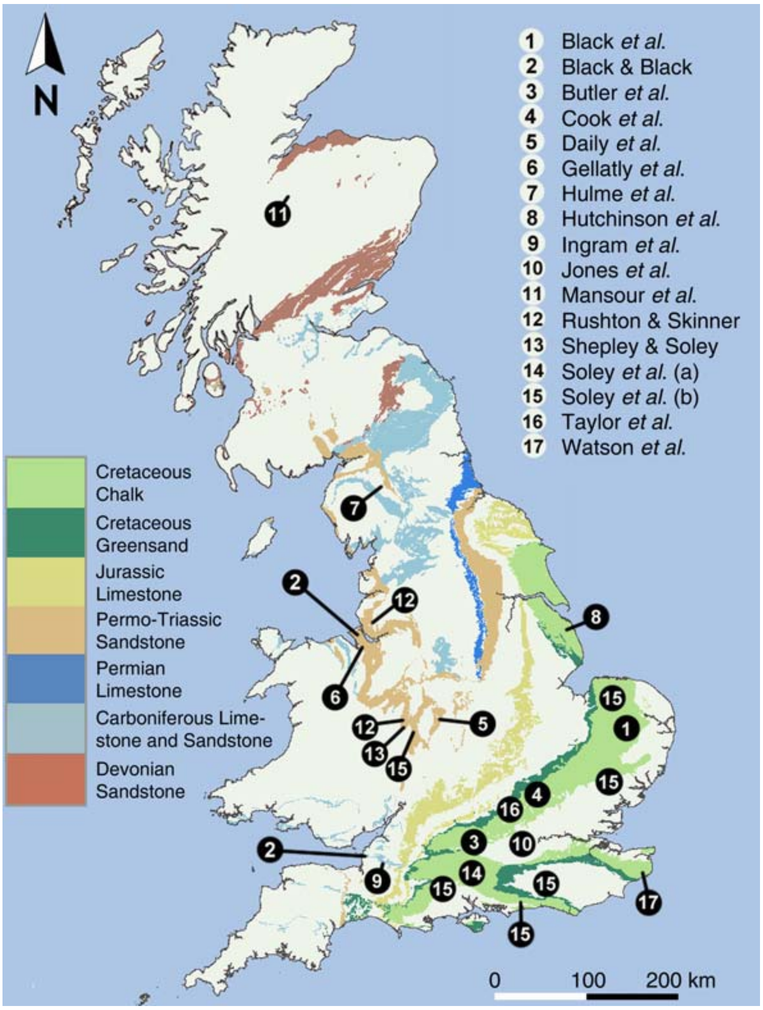

Fig. 3. Location map.

the England and Wales programme and the associated modelling mostly have seven common characteristics:

(1) the models simulate groundwater flow in large aquifer units, and are therefore termed 'regional' models;
(2) the models are time variant with distributed parameter fields;
(3) the models were generally built by consultants with technical steering by Environment Agency staff and external peer review, either by independent senior consultants or academics;
(4) stakeholders, such as the privatized water companies, participated in the projects to develop the regional models;
(5) calibration was done predominately on hydrometric time series dating from 1970 (systematic hydrometric monitoring in England and Wales was only implemented after the 1963 Water Resources Act (Downing 2004));
(6) in most cases the regional models simulate surface and groundwater flow and are therefore calibrated against gauged surface water flows as well as groundwater level hydrographs; and
(7) the models were commissioned for water resources purposes based on Environment Agency objectives focused primarily on groundwater quantity.

The last point in particular is important for understanding the *raison d'être* of the papers in this volume. As the work was commissioned based on regulatory need, the focus of the modelling is not on innovative science, but on applying sound science and delivering specific management results (or outcomes). These include water resources assessments, managing groundwater abstractions, estimating the impact of groundwater abstraction on river flows and wetlands and controlling saline intrusion. Consequently, the value of this work should be judged against the results in these areas as well as the science and the degree of innovation that has been generated. Some of the papers, such as Soley *et al.* (2012*b*) on the southern Chalk, provide broad overviews of the improvement in understanding that has been obtained from the modelling programme.

The driving forces for the modelling are discussed in Whiteman *et al.* (2012*a*), as well as the benefits forthcoming from the work. Hughes *et al.* (2012) provide examples of how non-expert stakeholders should be engaged to maximize the benefits.

Beyond the national modelling programme

As the Environment Agency has taken the lead on regional groundwater modelling, this is starting to open up the use of these regulatory tools by many other parties, principally the water companies for diffuse pollution issues and climate change predictions, but also environmental consultancies where the use is being extended to point source pollution. The use of MODFLOW for most Environment Agency regional models greatly facilitates this access, because it is freely available from the United States Geological Survey and widely used in the UK, and elsewhere internationally. However, water companies are in some cases still developing their own models for their specific purposes, as explained by Jones *et al.* (2012).

There is a strong contrast with Northern Ireland and Scotland where the equivalent government environmental regulators (Northern Ireland Environment Agency and Scottish Environmental Protection Agency) do not have similar programmes. Mansour *et al.* (2012) provide an account of the use of groundwater models in Scotland, where the British Geological Survey has had a prominent role.

The focus of the Environment Agency programme on groundwater quantity has been determined by the internal financial constraints of the Environment Agency, where the principle of financial 'ring-fencing' has, until recently, been applied to the water licensing income following the guidance of the UK government. In the Environment Agency the Water Resources function has been the main beneficiary of the charges raised from water licensing, which has consequently focused efforts on the water quantity aspects. Currently the most important water legislation is the Water Framework Directive (WFD) of the European Community (Council of European Communities 2000), for which Programmes of Measures are now being implemented through the 2009 River Basin Management Plans.

Research and future

The WFD has a particular emphasis on water quality and its effects on ecology, and it is likely that groundwater models will be needed for the prediction of temporal trends in concentrations of pollutants in the aquifers in three dimensions. Currently of particular concern are diffuse pollutants, particularly nitrates; an extensive review is provided of the nitrate problem in the UK and the scientific understanding in a 2007 thematic issue of the *Quarterly Journal of Engineering Geology and Hydrogeology* (Gooddy & Besien 2007).

The present volume also contains research papers on groundwater modelling from the UK academic community. Two of these papers consider major pollution incidents on the Chalk aquifer and the simulation of contaminant transport at a regional scale (Cook *et al.* 2012; Watson *et al.* 2012). These papers form a useful contrast with the papers written by the practitioners, as they give some insight into the ways in which the regional models of the Environment Agency can be used, improved and/or adapted to assess future trends in water quality. In the case of Cook *et al.* (2012), the contaminant transport model has been partly based on the Environment Agency regional groundwater model. Some of the academic papers also provide an insight into the information exchange between practitioners and academics. For example, the work described by Butler *et al.* (2012) is based partly on the work forthcoming from the Lowland Catchment Research (LOCAR) programme of the National Environment Research Council (NERC) and was supported by the Environment Agency.

It is anticipated that the six-yearly River Basin Management Plans of the WFD will provide the legal driver for further investment, as the 'status' of the aquifers (groundwater bodies in WFD terminology) will have to be assessed from a water quantity and quality perspective. Review of conceptual and numerical models for each six-year cycle is an implicit requirement of this process (Council of European Communities 2009). It is particularly the realization of demonstrable benefits that will determine the amount of future investment in the models and uptake of research. Such future investment could be limited to the updating of time series, or might involve extensive improvement of the models as the conceptual understanding improves with time. Making the groundwater models accessible to the wider hydrogeological community could be a key step in this process. A start has been made in England and Wales with the development of a map-based, client–server system for holding groundwater models (the National Groundwater Modelling System, see Whiteman *et al.* 2012*b*), which facilitates the access and running of models. The future success of this system should see a continued trend of greater utilization and reliance on groundwater models for water resources management in the UK.

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